



Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

Full Scale Trials of Dolosse to Destruction

Burcharth, Hans F.

Publication date:
1980

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):
Burcharth, H. F. (1980). *Full Scale Trials of Dolosse to Destruction*. Laboratoriet for Hydraulik og Havnebygning. Bulletin No. 17

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Michael Dorn

BULLETIN NR. 17
HANS F. BURCHARTH
FULL SCALES TRIALS OF
DOLOSSE TO DESTRUCTION

AALBORG UNIVERSITETSCENTER
LABORATORIET FOR HYDRAULIK OG HAVNEBYGNING
SOHNGARDSHOLMSVEJ 57 DK-9000 AALBORG DANMARK

INSTITUTE OF CIVIL ENGINEERING

AALBORG UNIVERSITY

Sohngårdsholmsvej 57 DK-9000 Aalborg DENMARK TEL (08) 142333

Hans F. Burcharth

FULL SCALE TRIALS OF DOLOSSE TO DESTRUCTION

MAY 1980

(Presented at the 17th International Conference on Coastal Engineering, 1980)

CONTENTS

Abstract	page 1
1. Introduction	- 2
2. Test Set up	- 3
3. Test Procedure	- 6
4. Test Programme	- 7
5. Theoretical Background for Analysis of the Tests	- 10
5.1 Dimensional Analysis of Impact	- 10
5.2 Drop Test Formular	- 10
5.3 Pendulum Test Formular	- 11
5.4 Analysis of the Influence from Cracks on the Dynamic Strength	- 12
6. Test Results	- 13
6.1 Unreinforced Units	- 13
6.2 Reinforced Units	- 15
7. Conclusions and Recommendations	- 16
8. Acknowledgements	- 20
9. References	- 20

FULL SCALE TRAILS OF DOLOSSE TO DESTRUCTION

by

Hans F. Burcharth*

ABSTRACT

It is well known that the relative dynamic strength of unreinforced slender concrete units decreases as the size increases. Big units can resist relatively smaller movements than small units. When model tests of cover layer stability are performed the determination of the damage criterion that should be adopted must therefore be based on knowledge of the dynamic strength of the corresponding prototype units.

With the purpose of establishing a relation between the size and the dynamic strength of unreinforced units some full scale tests to destruction of 1.5 and 5.4 t units were performed. The set up and the procedure of the tests which simulates the impact from rocking of the units and from concrete pieces that are thrown against the units are designed to make a comparison between the behaviour of units of different sizes possible. The test method is described and proposed as a standard method.

The theoretical expression for the dynamic strength is compared with the test results and it is shown that if the units are allowed to move there is an upper limit for the size of unreinforced units where a balance between the hydraulic stability of the cover layer and the strength of the units exists. Different ways of improving the strength of the units are discussed on the basis of the results from tests with different types of concrete.

The tests included an investigation of the influence of reinforcement, and of different types of concrete and surface cracks on the performance of the units.

* Prof. of Marine Civil Engineering, Aalborg University, Denmark

1. INTRODUCTION

It is well known that rubble mound breakwaters with armour layers of relatively small Dolos units - say up to 10 tons weight - have proved to be very successful structures, while there have been problems in a number of cases where very big Dolos units have been used.

There are probably many reasons to account for this. This paper deals with one of them, which could be expressed as the "lack of balance between the hydraulic stability of the units and their physical strength".

From hydraulic model tests it is known that the hydraulic stability of Dolos armour layers is extremely good if we allow the units to move, and usually a damage criterion is adopted where rocking of a number of units and displacement of a few units take place. The model units can be moved around during the tests without going into pieces, but in nature it is different as we know from experience that especially big slender units cannot resist much movement.

Unfortunately nobody has been able to make model block material with strength properties scaled correctly and it is doubtful whether it can be done at the moment at reasonable costs as for theoretical reasons both the compression and the tensile strength, the density and the dynamic Young's modulus must be controlled in a certain combination.

In 1978 the Hydraulics Laboratory, Ottawa, Canada made a very good attempt to simulate the strength by inserting a thin slice of a weak material into the stem of the model units, but correct, quantitative data cannot be obtained from this type of model units.

There is, therefore, a missing link. This in fact makes it impossible to apply the model test results directly for the design of big, slender concrete units, and at the moment sufficient practical experience of the behaviour of these units does not exist.

On this background some full scale tests of the dynamic strength of 1.5 and 5.4 t Dolos units have been performed with the purpose of getting a better understanding of the behaviour of big units and thereby find ways for an improvement of the units.

2. TEST SET UP

Two different types of tests were used. A drop test, which simulates the wave introduced rocking of the units, and a pendulum test, which simulates the impact from pieces of broken units that are thrown around by the waves.

Figure 1 shows the drop test and Figure 2 the pendulum test.

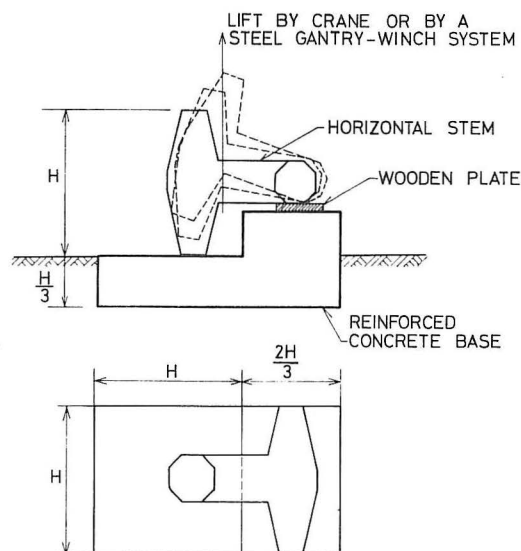


Figure 1 Drop test set up

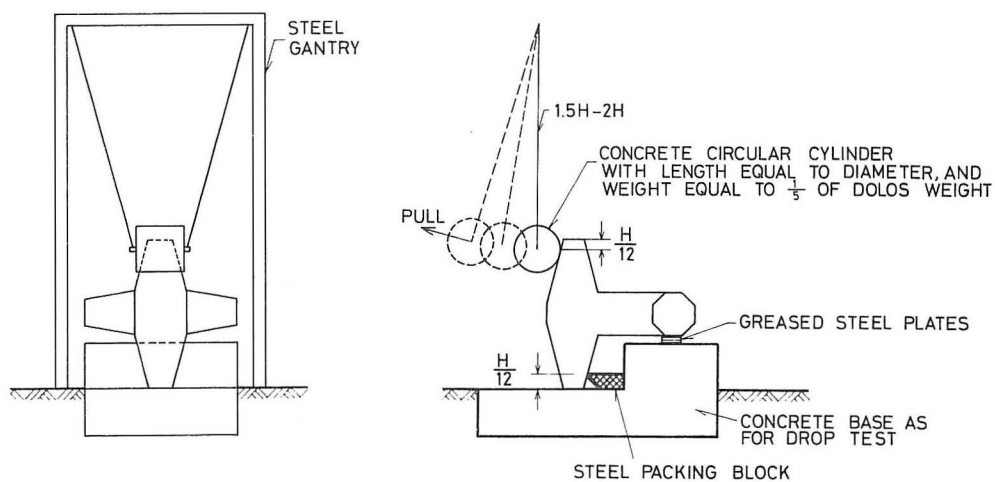


Figure 2 Pendulum test set up

In the drop test one end of the unit is lifted a predestinated height and then dropped by means of a quick release hook. In the pendulum test the weight is pulled back a certain distance and then released.

From practical experience it is known that in most cases when a Dolos is damaged it is fractured through the stem at a position close to the fluke. Therefore, the support of the unit and the direction and point of attack of the hitting force must be chosen in such a way as to ensure breakage in the stem. Besides this the support system should be well defined, thus allowing for the calculation of stresses in the unit. Figure 1 and Figure 2 show set up systems that make allowance for these points of view.

It is seen from the figures that all the dimensions of the test rig and the pendulum weight are related to the size of the Dolos unit. The idea is to introduce a standard method that makes it easier to compare the behaviour of units of different sizes, cf. the theory in chapter 5. This is a very important point since it is known that the strength of relatively small units is satisfactory, and by testing such small Dolosse and comparing the results with the results from tests of bigger Dolosse one can obtain information on the relations between the strength and the size and material of the units. Only if based on such information can a relation be established between the size of the units and the damage criterion which should be used in the hydraulic model tests.

The horizontally placed stem has the advantage that the height to which the unit can be lifted in the drop test without shifting the point (or line) of support is sufficient to ensure fracture. The unit will also hit the base with the full area of the fluke end and thus prevent that crushing in the contact zone takes place. The base should be made of good quality reinforced concrete to avoid cracking after a few drop tests.

Full scale drop tests of Dolos units have been performed by others before the tests described in this paper. But to the author's knowledge the test set up has been as shown in Figure 3. Here the unit is resting on the ground or on a relatively thin steel or concrete slab and one end of the unit is lifted and dropped.

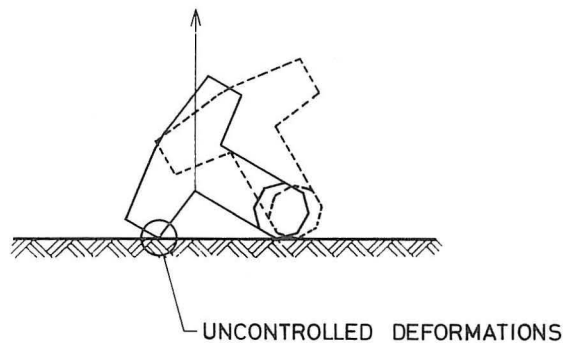


Figure 3 Inappropriate drop test set up

However this set up makes it impossible to compare different test results. This is mainly because the impact force will not be well defined, since the deformation from the crushing of the end of the Dolos leg and the deformation of the ground vary too much. Moreover, a test procedure where the threshold of the fall height is determined by increasing the fall height gradually cannot be used because of the uncontrolled crushing of the Dolos.

It may be argued that also the set up shown in Figure 1 implies uncontrolled impact forces caused by unknown variations in the soil characteristics at different sites. This is true, but for practical and economic reasons a much thicker concrete base, which is desirable, is not realistic. It is believed that the proposed relatively heavy and thick base will ensure applicable results as long as the base is founded on normal soils.

As the purpose of the pendulum test is to simulate the impact from a piece of a Dolos, e.g. a leg, thrown around by the waves a pendulum weight of $1/5$ of the Dolos weight is chosen. From an experimental point of view the same weight is adequate when combined with a pendulum length of 1.5 to 2 the Dolos height, since the draw back distance - or lifted height - of the pendulum required to destruct the unit will then be of a magnitude that can be measured accurately.

The pendulum should be made of the same type of concrete as used for the units and should be cast in a steel plate cylinder with wall

thickness of approximately 1/50 of the pendulum diameter. The steel cylinder serves as a mould and prevents damage of the surface from taking place during the tests.

A control of the impact energy from the pendulum is possible only if the movement of the pendulum when released is guided to ensure a central hit. The pendulum is therefore suspended in two non-parallel wires, the length of which should not be more than twice the Dolos height, see Figure 2. In this respect it is also important to use a good quality trigger mechanism (quick release hook) which does not cause undesirable movements of the pendulum when released. The mutual position of the Dolos and the pendulum should be so that the pendulum, when hanging at rest in vertical wires, should just touch the Dolos.

3. TEST PROCEDURE

Before the tests the surface of the units was carefully examined and photos were taken of possible surface cracks.

Since the influence of the load history on the dynamic strength was not known the load history was kept the same for each size of units. The history was chosen in such a way that failure occurred after approximately 6 to 8 impacts. In the drop tests the fall height, which was defined and measured as the vertical distance from the base to the centre of the fluke end, was gradually increased. For the 5.4 t units the initial drop was 100 mm, the second drop was 150 mm, and thereafter the increment was 20 mm. In the pendulum tests for the 5.4 t units the draw back distance, which was defined and measured as the shortest distance between the surface of the weight and the struck point on the Dolos unit, was gradually increased from 400 mm in the first strike to 450 mm in the second strike, and thereafter in increments of 20 mm.

Because of the rebound the unit was jerked back against the steel packing block after each pendulum blow.

The concrete surface was carefully examined after each stroke and in the case of reinforced units the width and the extent of the cracks were registered.

For the unreinforced units failure was taken as occurring at the first sign of fine cracks appearing in the unit. By soaking the unit with water these fine cracks could be seen as dry lines as the water was sucked by capillary action into the cracks.

With the purpose of examining the fracture the loading was continued until the unit broke into two pieces.

Where the fracture went through the surface cracks that existed before the test started the approximate extension of these cracks could be seen as wet areas.

For the reinforced units failure was taken as occurring when the crack width exceeded 0.1 mm. According to recent investigations of concrete structures in the North Sea this is a conservative value where no corrosion takes place.

For each unit the age and the specifications and density of the concrete mix were registered. The tensile strength was found indirectly from cylinder splitting tests and/or estimated from cylinder or cube compression strengths. The dynamic modulus of elasticity (the dynamic Youngs modulus) was found partly from the measurement of the velocity of ultrasonic pulses in the concrete and partly from static stress - strain graphs.

4. TEST PROGRAMME

Besides some pilot tests a total of 62 units were tested. Of these 27 were 1.5 t units and 35 were 5.4 t units. The tests were divided into

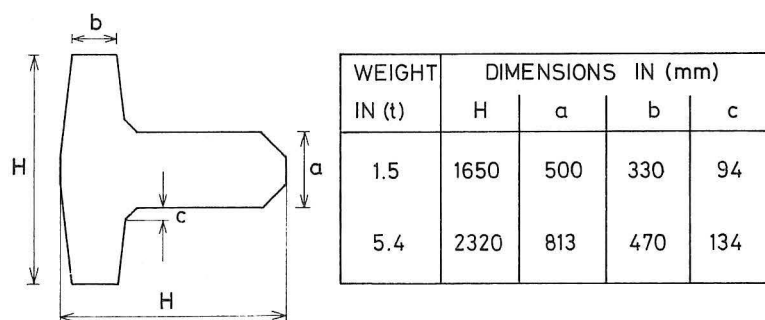


Figure 4 Geometry of Dolos units

6 series each containing approximately 10 units, of which one half was used for drop tests and the other half for pendulum tests. The geometry of the units is shown in Figure 4 and the specifications for the different series are given in Table 1.

Series No.	1	2	3	4	5	6
Weight of unit $M(\text{kg})$	1500	1500	1594	—	5400	—
Density $\rho(\text{kg mm}^{-3})$	$2.33 \cdot 10^{-6}$	$2.33 \cdot 10^{-6}$	$2.47 \cdot 10^{-6}$	—	$2.4 \cdot 10^{-6}$	—
Height of unit $H(\text{mm})$	—	1650	—	—	2320	—
Waist ratio $\alpha = a/H$	—	0.303	—	—	0.350	—
Weight of pendulum $m(\text{kg})$	—	294	—	—	990	—
Cement content (kg m^{-3})	291	291	392	—	385	—
Water-cement ratio	0.50	0.55	0.24	0.46	0.46	0.44
Aggregate	— Not crushed, max. 32 mm —			— Crushed basalt, max. 40 mm —		
Additives	4-5% air	4-5% air	78 kg fine particles (mainly Silicadust) and 23 kg plasticizer per m^3	$\frac{1}{2}\%$ Plasto- crete OC	$\frac{1}{2}\%$ Plasto- crete OC	4-5% air and $\frac{1}{2}\%$ Plasto- crete OC
Mean static compression strength; 100 x 200 mm cylinder. $\sigma_C(\text{N mm}^{-2})$	28.9	26.6	88.4	45.5*)	45.5*)	39.2*)
Mean static tensile strength; cylinder splitting test. $\sigma_T(\text{N mm}^{-2})$	2.95**)	2.79**)	5.74**)	4.38***)	3.56***)	4.18***)
Mean dynamic modulus of elasticity $E(\text{N mm}^{-2})$	$3.6 \cdot 10^4$	$3.6 \cdot 10^4$	$7.0 \cdot 10^4$	$5.2 \cdot 10^4$	$4.96 \cdot 10^4$	$4.50 \cdot 10^4$
Particulars	Reinforcement of stem, see Figure 6			Cracks in stem-fluke corners, see Figure 5		

*) Calculated from 150 mm cube tests by multiplying the cube strength by 0.74.

***) Determined from cylinders cast during the production.

***) Determined from cores taken from the units.

Table 1 Specifications of the test series

As seen from Table 1 different concrete mixes with a considerable variation of the strength properties were used. Also a test series with units exhibiting serious surface cracks in the stem fluke corners was performed.

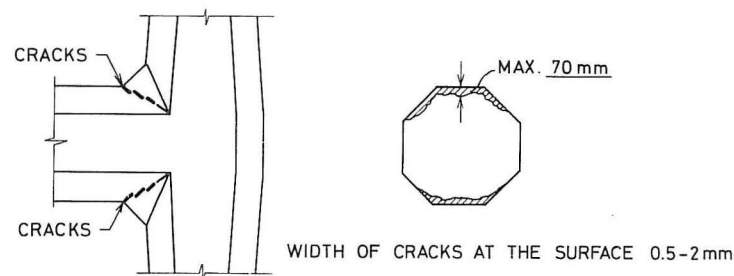


Figure 5 Typical extension of surface cracks in test series No. 5

Different degrees of reinforcement were used in some of the 1.5 t units with the purpose of investigating the relation between development and sizes of cracks and degree of reinforcement, see Figure 6. Because of limitations in the test program only the stem, being the weaker part of the unit, was reinforced. As a reinforced stem is much stronger than an unreinforced leg these tests could also give information about the dynamic strength of unreinforced legs. The concrete cover layer thickness was chosen to 70 mm in accordance with recommendations for concrete structures in the North Sea.

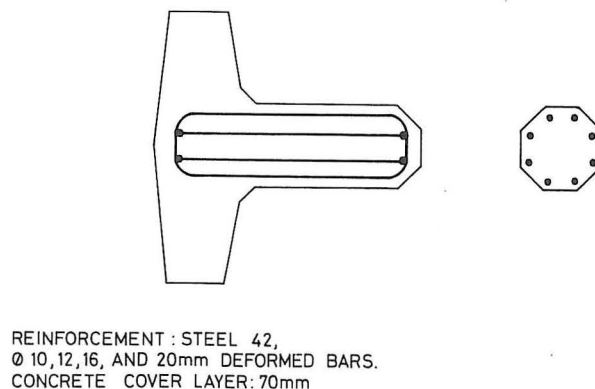


Figure 6 Reinforcement of 1.5 t Dolos units in test series No. 2

5. THEORETICAL BACKGROUND FOR ANALYSIS OF THE TESTS

5.1 Dimensional Analysis of Impact.

Consider a class of geometrically similar systems, in which the size of a structure and the size of an impinging body are both determined by a characteristic length and both made of the same material.

If the moving body strikes the structure the maximum stress σ at any point of the structure depends on the mass m and the velocity V of the incident body, the characteristic length L , the elastic modulus E , Poisson's ratio ν , and the mass density ρ . As an approximation E and ν are taken as constants that characterize the material, which means that the effects of rate of strain on stress are not taken into account.

By dimensional analysis we obtain,

$$\frac{\sigma}{mV^2L^{-3}} = f\left(\frac{EL^3}{mV^2}, \frac{m}{\rho L^3}, \nu\right) \quad (1)$$

As the proposed test system implies a constant ratio between the masses of the impinging body and the structure, and also because ν has a negligible influence on the phenomenon (we are dealing with concrete mixes with small variations in ν) equation (1) takes the simpler form,

$$\frac{\sigma}{mV^2L^{-3}} = f\left(\frac{E}{\rho V^2}\right) \quad (2)$$

This equation can be used to describe both the drop test and the pendulum test.

5.2 Drop Test Formular

In the case of the drop test the unit itself is the impinging body having a mass of M and a potential energy of Mgh , when the unit's centre of gravity is lifted vertically a distance h . As $V^2 = gh$ equation (2) yields,

$$\frac{\sigma}{MghH^{-3}} = f\left(\frac{E}{\rho gh}\right) \quad (3)$$

Until now only geometrically similar units have been considered. However, Dolos units are not always geometrically similar since the waist ratio $\kappa = a/H$ (see Figure 4) varies from 0.30 to 0.35 or more. By calculating the unit's momentum as a function of M , H , κ and h and taking the duration of the impact as proportional to H/c , where $c = \sqrt{E/\rho}$ is the speed of a longitudinal wave in the concrete, an expression for the mean impact force can be established. From this the maximum stress in the stem cross section close to the fluke corner is found to,

$$\frac{\sigma}{MghH^{-3}} = C \frac{1+\kappa}{\kappa^2} \sqrt{\frac{E}{\rho gh}}, \quad 0.3 \leq \kappa \leq 0.4 \quad (4)$$

where C is a constant factor. Equation (4) does not include the negligible stresses caused by the weight of the unit.

5.3 Pendulum Test Formular

In this case the impinging body is a pendulum with a mass m equal to or approximately equal to 1/5 of the mass of the Dolos unit. The potential energy of the pendulum is mgh when pulled back to a position where the centre of gravity is lifted vertically a distance h . The maximum velocity of the pendulum is $V = \sqrt{2gh}$. Equation (2) is valid only if the size of the pendulum and the Dolos are both determined by a characteristic length. Since Dolos units have varying waist ratios and also because the size and the weight of the pendulum for practical reasons are not always fixed parts of the size and the weight of the Dolos, equation (2) is not suitable for practical calculations. By using the same assumptions and calculation procedure as described for the drop test the following formula for the maximum stress in the stem cross section close to the fluke corner is obtained,

$$\frac{\sigma}{mghH^{-3}} = K \frac{1}{\kappa^3} \sqrt{\frac{E}{\rho gh}}, \quad (5)$$

where K is a constant factor. Equation (5) does not include the negligible stresses caused by the weight of the unit.

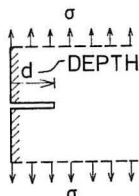
5.4 Analysis of the Influence from Cracks on the Dynamic Strength

The influence from cracks on the strength of the units can be looked into by means of fracture mechanics theory. An estimate on this influence can be made by using the fracture toughness parameter K_{IC} (critical stress intensity factor) for a static load situation on a linear elastic body of homogeneous and isotropic material. In K_{IC} the subscript I refers to the crack opening mode of crack propagation and the subscript C refers to the critical value of K_I , i.e. the onset of rapid fracture.

Although the assumptions related to K_{IC} are incorrect for concrete, many investigators have generally assumed that the approximations involved in the application of linear elastic fracture mechanics to concrete are reasonable.

For concrete K_{IC} values are found in the range from about 0.45 to 1.40 $\text{MN m}^{-3/2}$ for a static load situation. As an approximation the static load theory and the mentioned range of K_{IC} values are assumed valid for a dynamic load situation.

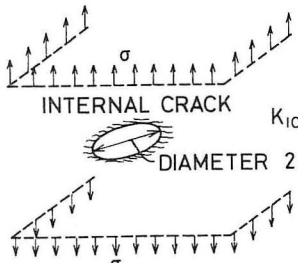
For plain strain conditions the critical sizes of surface cracks and internal cracks can be found from the equations (6) and (7), (see Figure 7), in which σ is the tensile stress at some distance from the crack.



DEPTH OF SURFACE CRACK

$K_{IC} = 1.2 \sigma \sqrt{\pi d}$

(6)



INTERNAL CRACK

DIAMETER $2d$

$K_{IC} = \frac{2}{\pi} \sigma \sqrt{\pi d}$

(7)

Figure 7 Fracture toughness parameters

As the tensile stress σ generally varies between 2.5 and 5 Nmm^{-2} the range of the critical crack sizes will be as shown in the diagram, Figure 8.

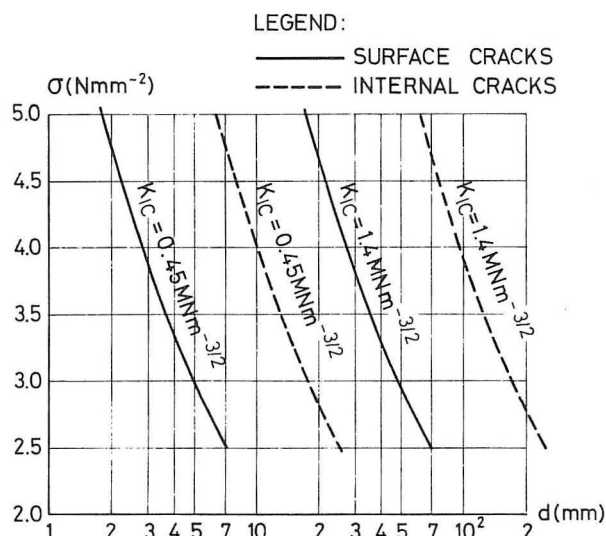


Figure 8 Critical sizes of surface cracks and internal cracks

It is seen from the graphs that if the tensile strength of the concrete is approximately 3 Nmm^{-2} and K_{IC} is in the range from 1 to 1.4 $\text{MNm}^{-3/2}$ then the surface cracks can have depths of up to 25-50 mm without altering the performance of the unit.

6. TEST RESULTS

6.1 Unreinforced Units

The test results are summarized in Table 2. C and K are found by replacing the tensile stress by the static tensile strength in eq. (4) and eq. (5). This is an approximation but since it is believed that the ratio between the static and the dynamic tensile strength is constant the approximation is acceptable.

The average and the standard deviation of C are 0.16 and 0.02 respectively, and the average and the standard deviation of K are 0.69 and 0.14 respectively.

Series No.	1	3	4	5	6
Drop height h for centre of gravity in drop tests. Average (mm)	153	171	117	115	138
Stand.dev. (mm)	14.5	5.0	9.4	20.9	22.5
Lifted height h of pendulum in pendulum tests. Average (mm)	46.5	45.8	40.5	39.9	39.9
Stand.dev (mm)	2.9	4.0	1.9	2.2	2.1
C , factor in eq. (4)	0.128	0.165	0.184	0.155	0.174
K , factor in eq. (5)	0.469	0.681	0.807	0.677	0.835
α , average of angle of rotation in drop tests	$13^{\circ}8$	$15^{\circ}5$	$7^{\circ}5$	$7^{\circ}3$	$8^{\circ}9$

Table 2 Test results for unreinforced units

In the drop tests, the cracking started at the top of the stem and spread to the bottom of the stem leading to a fracture of the type shown in Figure 9. The start of the cracking at the top side instead of at the bottom side is due to the big horizontal momentum of the top leg caused by the pivoting of the unit. In a few of the drop tests (mainly in series No. 1) the fracture developed first through the middle part of the stem and not in the stem-fluke corner.

In the pendulum tests the cracking started at the bottom of the stem and spread to the top, leading to a fracture of the type shown in Figure 9.

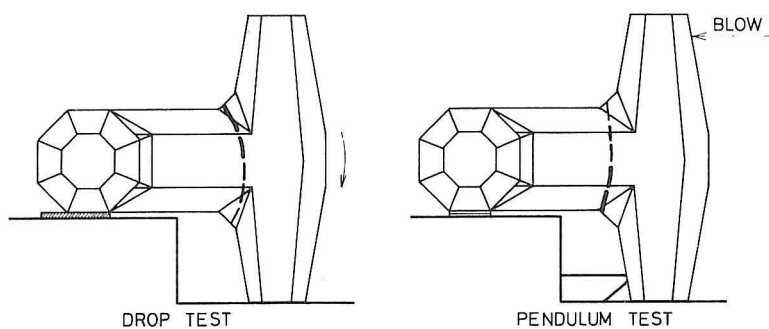


Figure 9 Typical fractures in unreinforced units

6.2 Reinforced Units

The results from test series 2 are summarized in Table 3 a and b.

Drop test No.	Reinforcement, deformed bars, steel 42		Drop height h for centre of gravity (mm)	Observations
	Size	%		
1	8 Ø10 mm	0.29	160	fine crack in stem
	-	-	174	fine crack in top leg
	-	-	222	top leg fractured, crack width in stem ≤ 0.1 mm
2	8 Ø12 mm	0.41	206	fine crack in stem
	-	-	238	crack in top leg
	-	-	268	top leg fractured, crack width in stem ≤ 0.07 mm
3	8 Ø16 mm	0.73	181	fine crack in top leg
	-	-	210	fine crack in stem
	-	-	286	bottom leg crushed, crack width in stem ≤ 0.01 mm
4	8 Ø20 mm	1.14	201	top leg fractured, no visible cracks in stem

Table 3 a Test results for reinforced units, Drop tests

Pendulum test No.	Reinforcement, deformed bars, steel 42		Lifted height h of pendulum (mm)	Observations
	Type	%		
1	8 Ø 10 mm	0.29	87	fine crack in stem top leg fractured, crack width in stem ≤ 0.1 mm
	-	-	112	
2	8 Ø 12 mm	0.41	119	fine crack in stem top leg fractured, crack width in stem ≤ 0.03 mm
	-	-	136	
3	8 Ø 16 mm	0.73	107	top leg fractured, no visible cracks in stem
4	8 Ø 20 mm	1.14	119	top leg fractured, no visible cracks in stem

Table 3 b Test results for reinforced units, Pendulum tests

Figure 10 shows typical positions of cracks in the reinforced units.

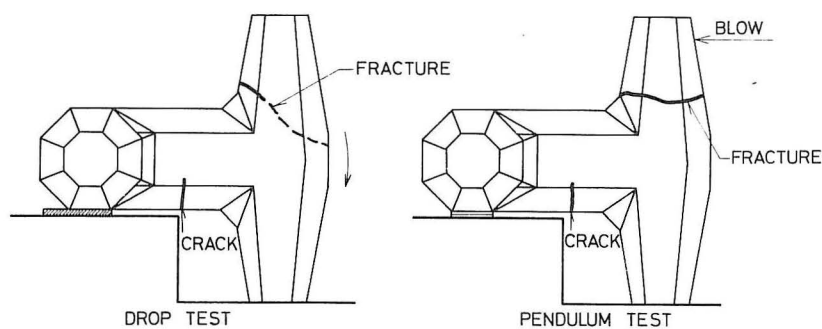


Figure 10 Typical cracks and fractures in reinforced units

7. CONCLUSIONS AND RECOMMENDATIONS

The presented theory for the dynamic loading of Dolos units should be regarded as a first approximation. In spite of this and in spite of the scatter in the values of C and K (Table 2), it is believed that the theory (eq. 4 and eq. 5) can be used to estimate the relative dynamic strength of units of different sizes, different waist ratios, and different concrete mixes. It should be noted that a considerable

scatter in the C and K values is expected because the determination of the tensile strength and of the dynamic modulus of elasticity is subject to big uncertainty. A careful determination of these two quantities is therefore an important part of the full scale tests.

Before a final conclusion about the presented theory can be made tests with big units (10-30 t) should be done and the influence of the load history should be investigated. This can be done by determination of the relation between the number of blows that will lead to fracture and different loads, e.g. 60%, 70%, 80% and 90% of the failure load that corresponds to the load history in the presented tests.

Both the test results and the theory show that the relative dynamic strength of unreinforced units decreases considerably with increasing size of the unit, other things being equal. Although the strength can be improved by increasing the waist ratio it is not always possible to compensate for the reduction of the strength. This can be explained by an example.

Let us assume that we know from experience that the dynamic strength of some 7.5 t Dolos units with a waist ratio of 0.3 is just sufficient to resist the rocking that takes place when the units are exposed to the design storm waves. Let us then assume that we perform some hydraulic model tests for a Dolos breakwater on a much more exposed place. In the model tests, units with a waist ratio of for example 0.34 is used, and from the tests it is concluded that the weight of the prototype units will be 52 t if the damage criterion that corresponds to the design wave situation for the 7.5 t units is used. For simplicity we will now assume that the same concrete mix is used for both sizes. From the drop test formula it is then found that the big Dolos unit must have a waist ratio of 0.39 to resist the same rocking - or angle of rotation - as the small units. From Figure 11 it is seen that by increasing the waist ratio that much, the shape of the unit is completely altered, and so is the hydraulic stability. Therefore, a new series of hydraulic model tests with more bulky Dolos units has to be done, but since such tests lead to a demand for even heavier units than the 52 t, a bigger waist ratio than 0.39 must be applied to obtain sufficient strength of the prototype units, etc.

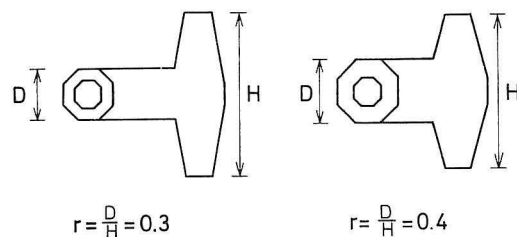


Figure 11 Influence of waist ratio on Dolosse of the same weight

From this it can be concluded that the design criterion which are adopted in hydraulic model tests must correspond to the dynamic strength of the prototype units.

Moreover it can be concluded that if a design criterion which implies movements of the units is adopted there will exist a maximum size of unreinforced units for which there is a balance between the hydraulic and the physical stability. Units heavier than this maximum size can, of course, be used if a non-rocking design criterion is adopted. However, this will lead to a demand for relatively heavier units.

From the test series No. 1 and No. 3 and from the theory it is seen that it is difficult to improve the dynamic strength by using a stronger concrete, even if a super-strong concrete, as the one in series No. 3, is used. This is so, because stronger concrete mixes are more brittle as they have relatively poorer tensile strength and relatively higher modulus of elasticity. It should be stressed that this conclusion must not lead to the use of weak concrete mixes, because the surface resistance and the long term durability of the units are very much dependent on the strength and the compactness of the concrete.

From a comparison of the test series No. 4 and No. 5 it can be concluded that an unreinforced unit can suffer from relatively deep surface cracks, even in the stem-fluke corners, without losing much of its dynamic strength. This matter, which can be explained by fracture mechanics theory, is caused by the low stress level and the relatively good fracture toughness of concrete. From the theory it can also be

concluded that even relatively big internal cracks have a negligible influence on the strength of the units. It should be noted that surface cracks should of course be avoided, since the freeze-thaw resistance and the long term durability of the units are affected by the cracks.

The age of the units, when tested, varied from 28 days to half a year. No correlation between age and dynamic strength was found.

On exposed locations, where very big armour units are needed, it is presumably advantageous to improve the dynamic strength by reinforcing the units. From test series No. 2 it can be concluded that, even with a small degree ($\leq 1\%$) of ordinary reinforcement, it seems possible to double the impact energy and still restrict the width of the cracks to sizes well below the critical size (0.1-0.3 mm), where corrosion of the bars takes place. This conclusion holds also for the more realistic situation where a unit, besides the dynamic loading, must carry a static load, e.g. from the weight of one or two other units. By comparing the test results from series No. 1 and No. 2 it is seen that the legs of a Dolos are considerably stronger than the stem. It is therefore a question whether it does pay to reinforce the legs (or some part of them) as it complicates the production of the units considerably. Very little is known about reinforced Dolosse, but in the few places where they have been used, e.g. in the Humboldt Jetties, investigations of the state including recording of the width of possible cracks should be performed.

Prestressed, posttensioned and fibre reinforced concrete are other possibilities, which should be looked at, but in this respect the importance of an easy production method should be stressed, since the production of ordinary Dolos units is difficult enough.

Although the described tests were performed with Dolos units the qualitative results and conclusions hold also for other types of slender concrete armour units.

8. ACKNOWLEDGEMENTS

The tests were performed in co-operation with mr. Hans Halskov (when a student at Aalborg University Center), The Danish Governmental Coast Authority, Aalborg Portland Cement and Concrete Laboratory, Denmark, South of Scotland Electricity Board, James Williamson & Partners, Scotland and Sir Robert Mc Alpine and Sons, U.K.

9. REFERENCES

- Beeby, A.W., 1978. Concrete in the Oceans, Cracking and Corrosion, Technical Report No. 1. Cement and Concrete Association, Department of Energy, U.K.
- Magoon, O.T., Shimizu, N., 1971. Use of Dolos Armour Units in Rubble-Mound Structures e.g. for Conditions in the Arctic. Proc. POAC Conf., 1971, Vol II, pp. 1089-1108.
- Mansard, E.P.D., Ploeg, J., 1978. Model Tests of Sines Breakwater. LTR-HY-67. Hydraulics Laboratory, National Research Council of Canada, Ottawa, Ont. Canada.
- Minders, S., Lawrence, F.V., Kesler, C.E., 1977. The J-Integral as a Fracture Criterion for Fiber Reinforced Concrete. Cement and Concrete Research, Vol. 7, pp. 731-742.